

Phenomenology of Heavy Flavors in Ultrarelativistic Heavy-Ion Collisions

A. A. Isayev

Kharkov Institute of Physics and Technology,

Academicheskaya Street 1, Kharkov, 61108, Ukraine

Kharkov National University, Svobody Sq., 4, Kharkov, 61077, Ukraine

Abstract

Some recent experimental results obtained in collisions of heavy nuclei ($\sqrt{s} = 200$ GeV) at BNL Relativistic Heavy-Ion Collider (RHIC) are discussed. The probes of dense matter created in heavy-ion collision by quarkonia, D and B mesons containing heavy charm and beauty quarks are considered. The centrality, rapidity and transverse momentum dependences of the nuclear modification factor and elliptic flow coefficient are presented and their possible theoretical interpretation is provided.

I. INTRODUCTION

Lattice QCD (LQCD) calculations predict that at a critical temperature $T_c \simeq 170$ MeV, corresponding to an energy density $\varepsilon_c \simeq 1$ GeV/fm³, nuclear matter undergoes a phase transition to a deconfined state of quarks and gluons, called Quark-Gluon Plasma (QGP). At the modern collider facilities such as CERN supersynchrotron (SPS) (the nucleon-nucleon (NN) centre-of-mass energy for collisions of the heaviest ions is $\sqrt{s} = 17.3$ GeV), Relativistic Heavy Ion Collider (RHIC) at Brookhaven ($\sqrt{s} = 200$ GeV), and Large Hadron Collider (LHC) at CERN ($\sqrt{s} = 5.5$ TeV), whose heavy-ion program will start soon, heavy-ion collisions are used to attain the energy density, exceeding ε_c . This makes the QCD phase transition potentially realizable within the reach of the laboratory experiments. The objective is then to identify and to assess suitable QGP signatures, allowing to study the properties of QGP. To that end, a variety of observables (probes) can be used [1]-[4]. Further we will be mainly interested in heavy-flavour probes of QGP, i.e., utilizing particles having c- and b-quarks.

A special role of heavy $Q = (c, b)$ quarks as probes of the medium created in heavy-ion collision (HIC) resides on the fact that their masses ($m_c \approx 1.3$ GeV, $m_b \approx 4.2$ GeV) are significantly larger than the typically attained ambient temperatures or other nonperturbative scales, $m_Q \gg T_c, \Lambda_{QCD} = 0.2$ GeV [5]. This has several implications: (i) The production of heavy quarks is essentially constrained to the early, primordial stages of HIC. Hence, heavy quarks can probe the properties of the dense matter produced early in the collision. (ii) Thermalization of heavy quarks is "delayed" relative to light quarks. One could expect that heavy quarks could "thermalize" to a certain extent, but not fully on a timescale of the lifetime of the QGP. Therefore, their spectra can be significantly modified, but still retain memory about their interaction history, and, hence, represent a valuable probe. (iii) RHIC, and especially LHC experiments allow to reach very low parton momentum fractions x , where gluon saturation effects become important. Heavy quarks are useful tools to study gluon saturation, since, due to their large masses, charm and bottom cross sections are calculable via perturbative QCD and their yield is sensitive to the initial gluon density.

The heavy-flavor hadrons we will be interested in include: 1) open charm $D = (c\bar{q})$ and open beauty $B = (b\bar{q})$ mesons composed of a heavy quark $Q = (c, b)$ and a light antiquark $\bar{q} = (\bar{u}, \bar{d})$. These mesons could be sensitive to the energy density of the medium through the mechanism of in-medium energy loss; 2) hidden charm [charmonia= $(c\bar{c})$] and hidden beauty

[bottomonia= $(b\bar{b})$] mesons (called collectively heavy quarkonia) being the bound states of the charm quark-antiquark, or bottom quark-antiquark pairs, respectively. Heavy quarkonia could be sensitive to the initial temperature of the system through the dissociation due to color screening of the color charge that will be discussed later.

For detecting heavy flavor hadrons, different decay channels are used. At RHIC, in PHENIX and STAR experiments the measurement of the spectra of open heavy flavors is based on the measurement of the spectra of heavy flavor (HF) electrons and positrons $[(e^+ + e^-)/2]$ from the semileptonic decays like $D^0 \rightarrow K^- e^+ \nu_e$, $D^+ \rightarrow \bar{K}^0 e^+ \nu_e$, etc. These measurements are based on the fact that the decay kinematics of HF electrons/positrons largely conserves the spectral properties of the parent particles. Besides, the STAR experiment has the capability to directly reconstruct open heavy flavor mesons through the hadronic decay channels like $D^0(\bar{D}^0) \rightarrow K^\mp \pi^\pm$, $D^+ \rightarrow K^- \pi^+ \pi^+$, etc. At low transverse momentum, the STAR experiment also uses heavy flavor decay muons to provide open heavy flavor measurements. Quarkonia in both STAR and PHENIX experiments are detected through their dilepton decays $Q\bar{Q} \rightarrow e^+e^-$ (midrapidity), $Q\bar{Q} \rightarrow \mu^+\mu^-$ (forward rapidity).

II. HEAVY FLAVOR PROBES OF QGP: QUARKONIA

We begin the discussion of heavy flavor probes of QGP with heavy quarkonia. The question we would like to address is: What could happen with quarkonium yields in HIC if QGP is really formed?

Let us note that if the deconfinement phase transition really takes place in a dense medium created in HIC, then a color charge in the QGP will be screened analogously to the Debye screening of an electric charge in the electromagnetic plasma. As a result of color Debye screening of the heavy quark interaction in QGP, the binding energy of a bound state decreases and one can expect that this would lead to the suppression of quarkonium yields in HIC. This idea was first suggested by H. Matsui and H. Satz [6] who predicted that color Debye screening will result in the suppression of J/ψ meson ($c\bar{c}$ in the 3S_1 state, $M = 3.097 \text{ GeV}$) yields. After that, the J/ψ suppression was considered as one of the key probes for the QGP formation in heavy ion collisions. J/ψ is especially promising because of the large production cross-section and dilepton decay channels which make it easily detectable.

However, soon it was realized that besides melting J/ψ mesons in QGP due to the screening of the color charge, there are also a few competing mechanisms which could explain the suppression of J/ψ production in heavy-ion collisions. These mechanisms are referred to as cold nuclear matter (CNM) effects. The first CNM effect is the absorption of J/ψ by nuclear fragments from colliding nuclei. Let us consider, e.g., the proton-nucleus collision. Once produced in the hard primary parton processes, J/ψ has to cross the length L of nuclear matter before exiting the nucleus, and, when traversing nuclear matter, it can be absorbed by forthcoming nucleons of a nucleus. The production cross section of J/ψ in p - A collision can be parameterized as

$$\sigma_{pA}^{J/\psi} = A\sigma_{pp}^{J/\psi} e^{-\sigma_{abs}^{J/\psi} \varrho L}, \quad (1)$$

where $\sigma_{pp}^{J/\psi}$ is the production cross section of J/ψ in p - p collisions and $\sigma_{abs}^{J/\psi}$ is the nuclear absorption cross section. From the global fit to the data on charmonium production in p - A collisions the value of $\sigma_{abs}^{J/\psi}$ can be extracted, in particular, at SPS (NA50 experiment) it was obtained that $\sigma_{abs}^{J/\psi} = 4.2 \pm 0.5$ mb [7].

The second CNM effect is related to shadowing of low momentum partons. This means the depletion of low momentum partons in nucleons bound in nuclei as compared to free nucleons. This effect can be accounted for in terms of the modification of the parton distribution functions in nucleon within the nucleus with respect to the parton distribution functions in a free nucleon:

$$R_i^A(x, Q^2) = \frac{f_i^A(x, Q^2)}{f_i^N(x, Q^2)} < 1, \quad i = q_v, q_{sea}, g. \quad (2)$$

Here "i" denotes valence quarks, sea quarks, and gluons, x is the parton momentum fraction, Q^2 is the momentum transfer squared. At high energies, J/ψ s are dominantly produced through the gluon fusion, and the J/ψ yield is therefore sensitive to gluon shadowing. The underlying idea explaining the occurrence of gluon shadowing is that the gluon density strongly rises at small x to the point where gluon fusion, $gg \rightarrow g$, becomes significant. In the case of proton-nucleus and nucleus-nucleus collisions, where nuclei with large mass number A are involved, the nonlinear effects are enhanced by the larger density of gluons per unit transverse area of the colliding nuclei. A direct consequence of nuclear shadowing is the reduction of hard-scattering cross sections in the phase-space region characterized by small- x incoming partons. For gluons, e.g., shadowing becomes important at $x \lesssim 5 \times 10^{-2}$, and, hence, is relevant for the conditions of RHIC and LHC. Note however that the strength

of the reduction is constrained by the current experimental data only for $x \gtrsim 10^{-3}$.

Let us consider the J/ψ production at RHIC experiments. The J/ψ suppression can be characterized by a ratio called the nuclear modification factor

$$R_{AB}(p_T, y) = \frac{d^2 N_{J/\psi}^{AB}/dp_T dy}{N_{coll} d^2 N_{J/\psi}^{pp}/dp_T dy}, \quad (3)$$

obtained by normalizing the J/ψ yield in A - B nucleus-nucleus collision by the J/ψ yield in p - p collision at the same energy per nucleon pair times the average number of binary inelastic NN collisions. This ratio characterizes the impact of the medium on the particle spectrum. If heavy ion collision is a superposition of independent N_{coll} inelastic NN collisions, then $R_{AB} = 1$, whereas $R_{AB} < 1$ ($R_{AB} > 1$) corresponds to the case of the J/ψ suppression (enhancement). As we discussed already, at first, it is necessary to clarify the role of CNM effects on J/ψ production. At RHIC, CNM effects are studied in collisions of light deuteron and heavy gold nuclei, when the energy density reached in the collision is not enough for the formation of QGP. At RHIC energies, shadowing of partons is important and in the model calculations is implemented in two shadowing schemes for the nuclear parton distribution functions, the EKS model [10] and NDSG model [11]. The J/ψ break-up cross sections obtained for two shadowing schemes from the best fit to data are $\sigma_{\text{breakup}} = 2.8_{-2.1}^{+2.3}$ mb (EKS) and $\sigma_{\text{breakup}} = 2.6_{-2.6}^{+2.2}$ mb (NDSG) [12] (in Ref. [12], the term "break-up cross section" is used instead of the term "absorption cross section"). Although these values are consistent, within large uncertainties, with the corresponding value obtained at CERN SPS, a recent analysis [13] shows that, in fact, the level of J/ψ CNM break-up significantly decreases with the collision energy.

Let us now consider charmonium production in heavy ion collisions at RHIC. Figs. 1,2 show the p_T -integrated J/ψ nuclear modification factor obtained in Au-Au collisions at RHIC/PHENIX experiment as a function of centrality, parametrized by the number of participating nucleons at mid- and forward rapidities, respectively [12, 14]. The PHENIX data are shown by boxes. The R_{AA} approaches unity for the peripheral collisions (small N_{part}) and goes down to approximately 0.2 at most central collisions (large N_{part}). To see the level of the anomalous suppression beyond the cold nuclear matter effects it is necessary to extrapolate the CNM effects obtained in d-Au collisions to Au-Au collisions within the given shadowing scheme and corresponding J/ψ break-up cross section. The results are shown by black and red curves with the corresponding error bands. It is seen that J/ψ production

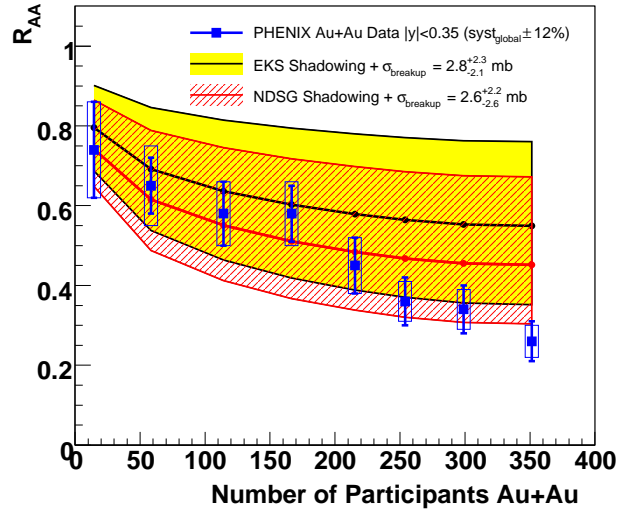


FIG. 1: (Color online) J/ψ 's R_{AA} for Au-Au collisions at midrapidity compared to a band of theoretical curves for the breakup values found to be consistent with the d -Au data. Both EKS and NDSG shadowing schemes are included.

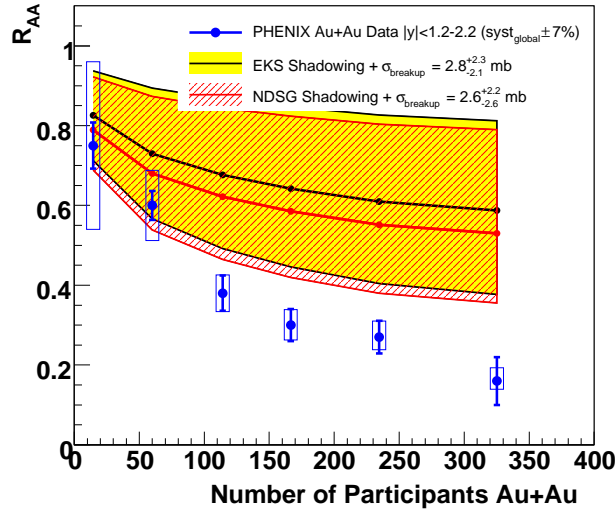


FIG. 2: (Color online) Same as in Fig. 1 but at forward rapidity.

is significantly suppressed beyond CNM effects at forward rapidity and suppression is less pronounced at midrapidity in most central Au-Au collisions.

Thus, one can conclude that assuming the conservative cold nuclear matter approaches some level of the anomalous suppression is indeed observed at RHIC which could characterize the produced medium as hot and deconfined.

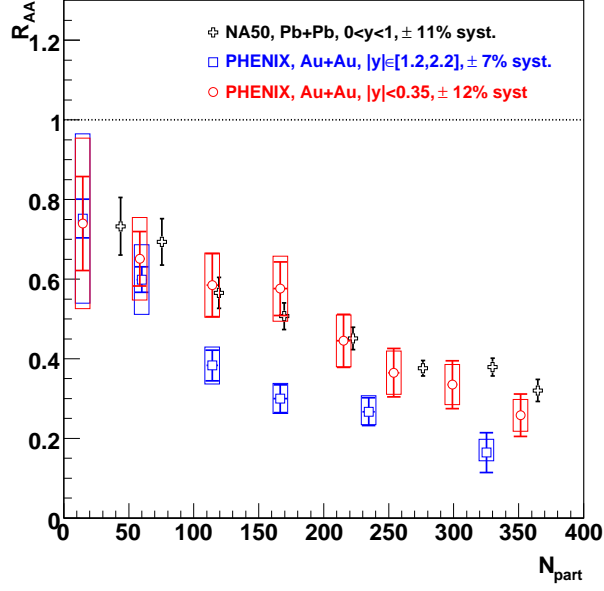


FIG. 3: (Color online) J/ψ nuclear modification factor for the most energetic SPS (Pb-Pb) and RHIC (Au-Au) collisions, as a function of the number of participants N_{part} .

However, not all is still clear. Measurements of the J/ψ suppression by PHENIX collaboration at RHIC lead to some surprising features. Fig. 3 shows compiled data for the nuclear modification factor obtained in CERN SPS and RHIC PHENIX experiments. There are two surprising results in these measurements. First, the mid rapidity suppression in PHENIX (the red boxes) is lower than the forward rapidity suppression (blue boxes) despite the experimental evidence that the energy density is higher at midrapidity than at forward rapidity, and, hence, one could expect that at midrapidity J/ψ will be more suppressed due to higher density of color charges. Secondly, the nuclear modification factor R_{AA} at midrapidity in PHENIX (red boxes) and SPS (black crosses) are in agreement within error bars, a surprising result considering that the energy density reached at RHIC is larger than the one reached at SPS. This indicates that at RHIC energies additional mechanisms countering the suppression, could be operative.

Let us consider possible explanations of the above features. 1. Regeneration of J/ψ in the hot partonic phase from initially uncorrelated c and \bar{c} quarks (quark coalescence model). If to compare the J/ψ suppression pattern at RHIC and SPS, J/ψ could be indeed more suppressed at RHIC than at SPS, but then regenerated during (or at the boundary of) the hot partonic phase from initially uncorrelated c and \bar{c} quarks. If to compare the results at

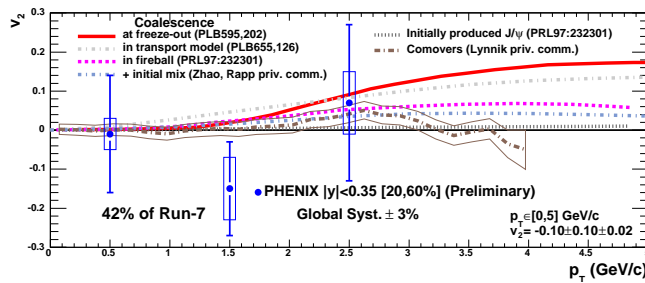


FIG. 4: (Color online) J/ψ 's v_2 at midrapidity for [20,60]% in centrality, as a function of p_T , using 42% of 2007 Au + Au statistics, with some theoretical predictions.

RHIC (midrapidity vs. forward rapidity), at midrapidity, due to the higher energy density, there are more c and \bar{c} quarks to regenerate than at forward rapidity that could explain the stronger suppression at forward rapidity. Note that the total number of initial $c\bar{c}$ pairs is larger than 10 in the most central Au-Au collisions. Certainly, if regeneration is important at the RHIC conditions, it will be even more important at the LHC conditions where more than 100 $c\bar{c}$ pairs is expected to be produced in the central Pb-Pb collisions. 2. J/ψ production could be more suppressed at forward rapidity due to the nuclear shadowing effects, which could be more pronounced away from midrapidity [15].

One of possible experiments aimed to verify the quark coalescence model is the measurement of the J/ψ elliptic flow [16]. The idea is that if charmonia were produced by coalescence of charm quarks, they should inherit somehow their flow, which is known to be quite large from the open heavy flavor measurements (see the next Section), resulting in a higher v_2 than in the case of the direct production of J/ψ in hard collisions. The PHENIX experiment reported a first tentative measurement of J/ψ 's v_2 in Au-Au collisions [17]. As is seen from Fig. 4, these proof-of-principle measurements at the current level of precision do not allow one to distinguish between models assuming various level of regeneration (and thus elliptic flow) and much larger statistics is probably needed to differentiate between different models.

To show the complexity of the problem, let us consider some theoretical models for the charmonium production, which quite satisfactory describe the RHIC data but whose predictions for LHC are drastically different. First, in the *statistical hadronization model* (SHM) [18], it is assumed that: 1. All heavy quarks (charm and bottom) are produced in primary hard collisions and their total number stays constant until hadronization. 2. Heavy quarks reach thermal equilibrium in the QGP before the chemical freeze-out (hadronization).

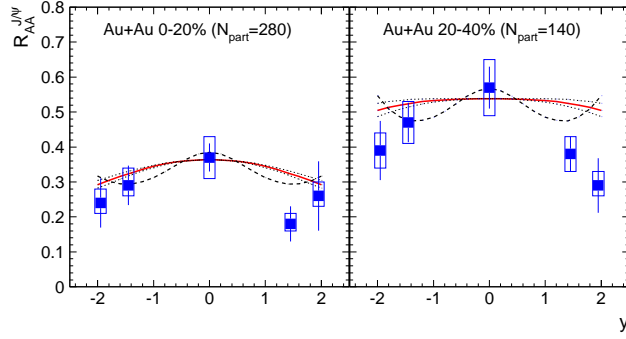


FIG. 5: (Color online) Rapidity dependence of $R_{AA}^{J/\psi}$ for two centrality classes in the statistical hadronization model. The data from the PHENIX experiment (symbols with errors) are compared to calculations (lines, see text).

3. All quarkonia are produced (nonperturbatively) through the statistical coalescence of heavy quarks at hadronization. Multiplicities of various hadrons are calculated with the grand canonical ensemble. The generation of J/ψ proceeds effectively if c, \bar{c} quarks are free to travel over large distances implying deconfinement.

Fig. 5 shows the rapidity dependence of the nuclear modification factor, obtained in this model and the comparison with the rapidity dependence at PHENIX for two centrality bins. Two theoretical curves correspond to two fitting procedures, with one and two Gaussians of the J/ψ data in pp collisions. In both cases, calculations reproduce rather well (considering the systematic errors) the R_{AA} data. The model describes the larger suppression away from midrapidity. The maximum of R_{AA} at midrapidity in this model is due to the enhanced generation of charmonium around midrapidity, determined by the rapidity dependence of the charm production cross section. The centrality dependence of R_{AA} at $y = 0$ is shown in Fig. 6. The model reproduces quite well the decreasing trend with centrality seen in the RHIC data. Fig. 6 also shows the prediction of the model for the LHC. At much higher LHC energies, the charm production cross section is expected to be larger by about an order of magnitude. As a result, a totally opposite trend as a function of centrality is predicted, with R_{AA} exceeding unity for central collisions.

Let us consider *the comovers interaction model* (CIM) [19]. This model does not assume the deconfinement phase transition. Anomalous suppression of J/ψ (beyond CNM effects) is the result of the final state interaction of the $c\bar{c}$ pair with the dense medium produced in the collision (comovers interaction). The model consistently treats the initial and final

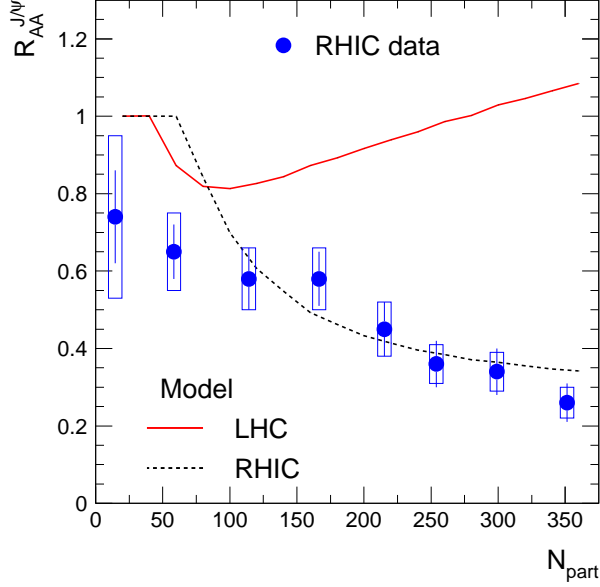


FIG. 6: (Color online) Centrality dependence of the $R_{AA}^{J/\psi}$ at midrapidity, according to the statistical hadronization model.

state effects. The initial state effects include: 1) nuclear absorption of the pre-resonant $c\bar{c}$ pairs by nucleons of the colliding nuclei, 2) consistent treatment of nuclear shadowing for hard production of charmonium. The final state effects include absorption of the $c\bar{c}$ pairs by the dense medium created in the collision (interaction with comoving partons or hadrons produced in the collision). The model does not assume thermodynamic equilibrium and, thus, does not use thermodynamic concepts. The density of charmonium is governed by the differential rate equation

$$\tau \frac{dn_{J/\psi}}{d\tau} = -\sigma_{co}[n_{co}(b, s, y)n_{J/\psi}(b, s, y) - n_c(b, s, y)n_{\bar{c}}(b, s, y)], \quad (4)$$

supposing a pure longitudinal expansion of the system and boost invariance. In Eq. (4), n_{co} is the density of comovers, which is found in the dual parton model [20] together with the proper shadowing correction, σ_{co} is the cross section of J/ψ dissociation due to interactions with comovers, taken such as to reproduce the low energy SPS experimental data (with $\sigma_{co} = 0.65$ mb). The first term on the right describes dissociation of charmonium due to interaction with comovers. The second term describes the recombination of charmonium and is proportional to the product of densities of charm quarks and antiquarks. The important

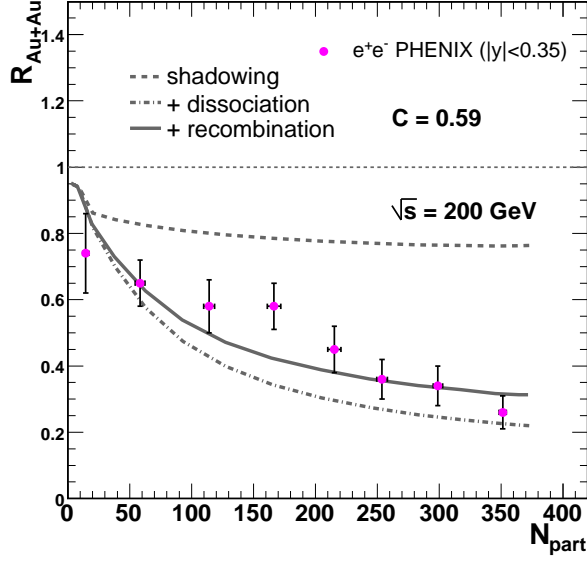


FIG. 7: Results for J/ψ suppression in Au-Au collisions at RHIC at midrapidity in the comovers interaction model. The solid curve is the final result. The dash-dotted one is the result without recombination ($C = 0$).

feature of the CIM is that recombination of $c\bar{c}$ quarks proceeds only locally, when the densities of quarks and antiquarks are taken at the same transverse coordinate s . This is different from the recombination in the SHM, where recombining quarks can be separated by large distance that implies deconfinement. The effective recombination cross section in the CIM is equal to the dissociation cross section due to the detailed balance. The results for the centrality dependence of the R_{AA} are shown in Fig. 7. At midrapidity, the experimental data are well reproduced by full theoretical calculations (solid curve) taking into account nuclear shadowing, dissociation by comovers and recombination from charm quark and antiquark pairs. The results at forward rapidity, presented in Fig. 8, also well agree with the data, in particular, the J/ψ suppression at forward rapidity is somewhat larger than the suppression at midrapidity.

Fig. 9 shows the predictions of the model for LHC. The parameter C encodes the recombination from $c\bar{c}$ pairs and vanishes in the absence of recombination. Although the density of charm grows substantially from RHIC to LHC, the combined effect of initial-state shadowing, absorption and comovers dissociation overcomes the effect of parton recombination. This is in sharp contrast with the predictions of the statistical hadronization model where

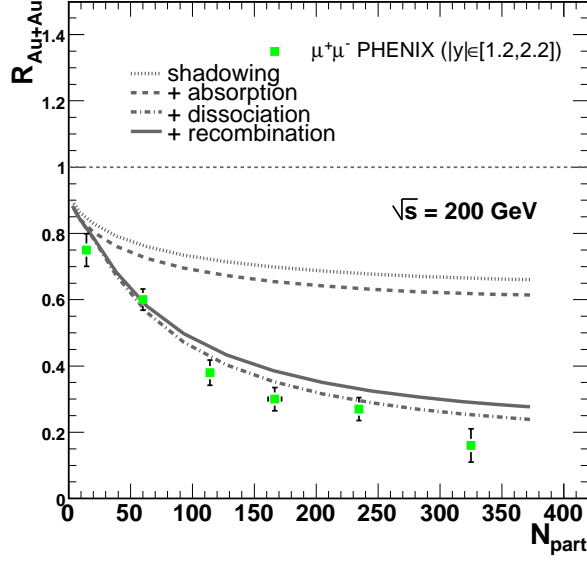


FIG. 8: Same as in Fig. 7, but at forward rapidity. The dashed line is the total initial-state effect. The dotted line is the result of shadowing. In Fig. 7, the last two lines coincide.

a strong enhancement of the J/ψ yield with increasing centrality was predicted.

Thus, the J/ψ suppression is an important characteristic to search for QGP. But if J/ψ anomalous suppression (beyond CNM effects) was observed in HIC, there are a few competing mechanisms to explain that: 1. Charmonium is dissociated due to the genuine color screening in the deconfined medium. 2. Charmonium is dissociated through interactions with comoving partons or hadrons in the medium formed in HIC. How to differ these mechanisms? In comovers interaction model, the anomalous suppression sets in smoothly from peripheral to central collisions rather than in a sudden way when the corresponding dissociation temperature in the deconfined medium is reached. Even at SPS, where the role of quark recombination is of minor importance, current experimental errors still do not allow to disentangle these two mechanisms. However, even if the color screening mechanism is dominating, it is unclear what is really melted, directly produced J/ψ s or originating from the feed-down of less bound charmonium states, χ_c ($\rightarrow J/\psi + X$), ψ' ($\rightarrow J/\psi + X$), which have lower dissociation temperatures. At RHIC and LHC conditions, the feed-down from B-meson decays becomes also important. Recombination enhances J/ψ production and much complicates the picture but its effect may be different depending on whether the deconfinement phase transition happened or not. It is even possible that after all J/ψ s were melted

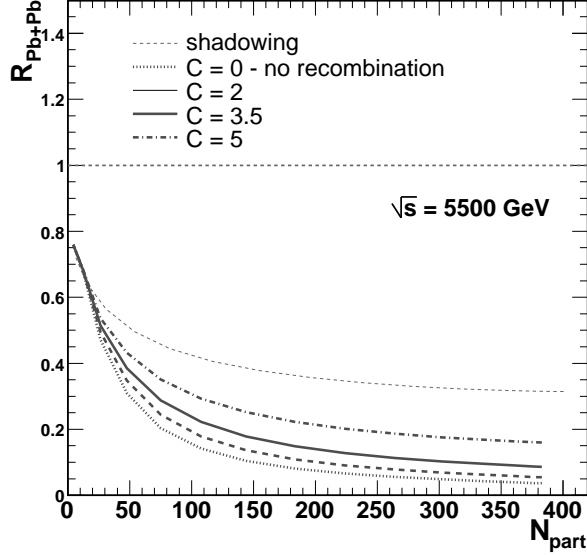


FIG. 9: Results for J/ψ suppression in Pb+Pb at LHC ($\sqrt{s} = 5.5$ TeV) at midrapidity for different values of the parameter C in the comovers interaction model. The upper line is the suppression due to initial-state effects.

in QGP they can be statistically regenerated at hadronization. True operative mechanisms of J/ψ production can be established only after studying all important dependences (from centrality, rapidity, collision energy \sqrt{s}, \dots) of all relevant observables with sufficient accuracy. Further we will consider also the J/ψ production in RHIC experiments as a function of the transverse momentum, but, for the sake of comparison, this will be more illustrative to do after presenting the respective dependence for open heavy flavor mesons.

So far we considered the suppression (or enhancement) patterns for the J/ψ production. Now let us briefly discuss the perspective for bottomonia. One could expect that bottomonium production might be easier to understand than charmonium production due to the following reasons. 1. Since less than one $b\bar{b}$ pair is produced in one central Au-Au collision, the regeneration is negligible at the conditions of RHIC. Besides, only about 5 $b\bar{b}$ pairs are expected to be produced in a single central Pb-Pb collision at LHC. Hence, regeneration should play much less role in the beauty sector than in the charm sector. 2. Having higher masses, bottomonia originate from higher momentum partons and will less suffer from shadowing effects. 3. The absorption cross section for Υ is by 40 – 50 % smaller than the corresponding cross section for J/ψ and ψ' .

These features should ease the separation of the anomalous suppression in the Υ 's family.

III. HEAVY FLAVOR PROBES OF QGP: OPEN HEAVY FLAVOR MESONS

What qualitative effects could one expect to obtain when probing the dense matter by heavy quarks (charm or bottom)? As well known from electrodynamics, the bremsstrahlung off an accelerated heavy quark Q is suppressed by the large power of its mass $\sim (m_q/m_Q)^4$ as compared to light quarks. Therefore, gluon radiation off heavy quarks (i.e., radiative energy loss) is much suppressed relative to light quarks. Consequently, one could expect a decrease of high p_T suppression and of the elliptic flow coefficient v_2 from light to charm to bottom quarks. Or, that the energy loss and coupling to matter of heavy quarks is smaller than for light quarks as well as that the thermalization time for heavy quarks is longer than for light quarks. Due to the above features, one should observe a pattern of gradually increasing R_{AA} when going from the mostly gluon-originated light-flavor hadrons (h^\pm and π^0) to D to B mesons: $R_{AA}^h \lesssim R_{AA}^D \lesssim R_{AA}^B$ [21] (gluons lose more energy than quarks since gluons have a higher color charge). The enhancement above the unity of the heavy-to-light ratio $R_{AA}^{D/h} = R_{AA}^D/R_{AA}^h$ probes the color charge dependence of the parton energy loss while the ratio $R_{AA}^{B/D} = R_{AA}^B/R_{AA}^D$ probes the mass dependence of the parton energy loss.

Let us now consider what the experiment tells us about the open heavy flavor p_T suppression and elliptic flow. As mentioned earlier, at RHIC, open heavy flavors can be studied through the measurements with the electrons and positrons originating from the semileptonic decays of D and B mesons. Fig. 10 shows the nuclear modification factor and elliptic flow coefficient for HF electrons as functions of p_T , obtained in central collisions of gold nuclei at RHIC (closed circles) [22]-[25]. In contrast to the above expectations, the results for R_{AA}^{HF} show a strong suppression of HF decay electrons at $p_T > 2$ GeV/c, approaching at high p_T the level of suppression for π^0 . This evidences that produced medium is quite dense for heavy quarks to lose energy as efficiently as light quarks do. The measurement of elliptic flow gives rather large value for v_2^{HF} . This means that HF electrons are involved in a collective motion being indicative of the collective flow of their parent particles as well.

In Fig. 10, the results of some model considerations are also shown. The best description is provided by the model assuming the Brownian motion of heavy quarks within the framework of Langevin dynamics [26]. Let us consider the basic assumptions of this theory. Firstly,

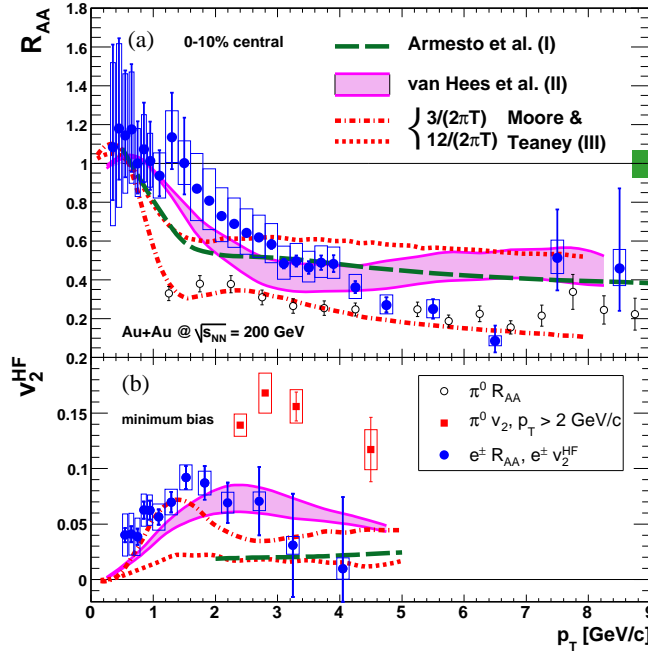


FIG. 10: (Color online) Nuclear modification factor (upper panel, central Au-Au) and elliptic flow (lower panel, minimum-bias Au-Au) of non-photonic electrons at RHIC, compared to theory. The band corresponds to the Langevin simulations based on an expanding fireball with effective heavy quark resonance interactions [26].

the thermal heavy quark momentum $p^2 \sim mT$ (in nonrelativistic approximation) is much larger than the typical momentum transfer $Q^2 \sim T^2$ from a thermal medium to a heavy quark. Hence, the motion of a heavy quark in the QGP can be represented as the Brownian motion, which can be described by using the Langevin equation. Secondly, heavy quark loses its energy in elastic scattering processes with light partons. Besides, as evidenced from calculations of heavy and light meson correlators within LQCD, in QGP the D - and B -meson like resonant states exist up to $T < 2T_c$. Rescattering on these resonant states plays an important role in thermalizing heavy quarks. Thirdly, in order to get the spectrum of HF electrons, c - and b -quarks are to be hadronized to D and B mesons via quark coalescence (at low p_T) and fragmentation (at high p_T).

The analysis shows that resonance scattering decreases nuclear modification factor R_{AA}^{HF} and increases azimuthal asymmetry v_2^{HF} . Heavy-light quark coalescence in subsequent hadronization significantly amplifies v_2^{HF} and increases R_{AA}^{HF} , especially in the $p_T \simeq 2$ GeV/c region. The contribution from B mesons to R_{AA}^{HF} and v_2^{HF} is estimated by providing full calcu-

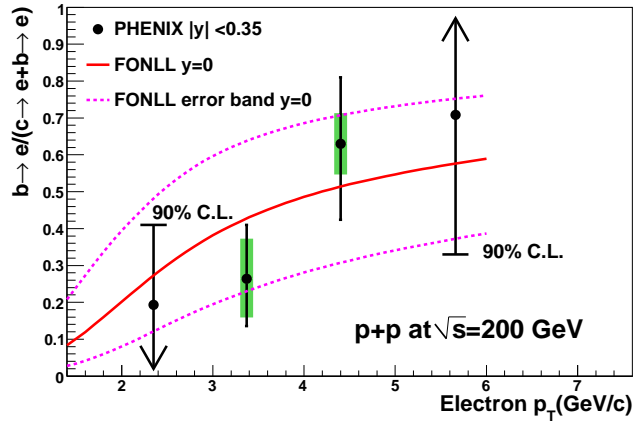


FIG. 11: (Color online) Transverse momentum dependence of the relative contribution from B mesons to the non-photonic electron yields. The solid curve illustrates the fixed-order-plus-next-to-leading-log (FONLL) calculation [28].

lations with $c+b$ quarks and with only c quarks. The result is that the B-meson contribution increases R_{AA}^{HF} and decreases v_2^{HF} , and becomes important above $p_T \simeq 3$ GeV/c. The last point was actually confirmed in the recent PHENIX measurements of the bottom fraction of HF electrons, $(b \rightarrow e)/[(b \rightarrow e) + (c \rightarrow e)]$, obtained in p - p collisions at $\sqrt{s} = 200$ GeV and shown in Fig. 11 [27]. Thus, one can conclude, that the combined effect of coalescence of heavy quarks Q with light quarks q , and of the resonant heavy-quark interaction is essential in generating strong elliptic flow v_2^{HF} of up to 10%, together with strong suppression of heavy flavor electrons with R_{AA}^{HF} about 0.5.

IV. CHARMONIUM PRODUCTION AT FINITE TRANSVERSE MOMENTUM

Now we can consider the production of J/ψ mesons at finite transverse momentum p_T and compare it with the corresponding dependence for open heavy flavor mesons. Fig. 12 shows the p_T -dependence of J/ψ 's R_{AA} in 0 – 20% Cu+Cu collisions from PHENIX [29] and STAR [30], and 0 – 60% Cu+Cu collisions from STAR [30]. The most striking peculiarity is that the nuclear modification factor for J/ψ increases with p_T from the value of about 0.5 at low p_T to the value slightly exceeding unity at high $p_T > 5$ GeV/c. These data indicate that there is no J/ψ suppression at high p_T in heavy-ion RHIC experiments - the result which could be considered as surprising taking into account the strong suppression of heavy flavor

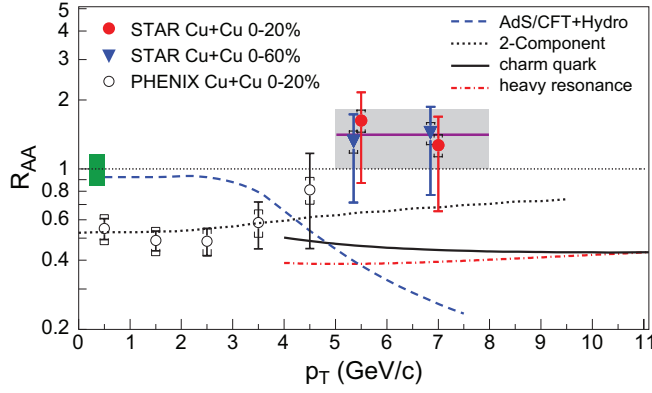


FIG. 12: (Color online) J/ψ 's R_{AA} vs. p_T , obtained at RHIC experiments and compared with different model calculations. The best description of the data is provided by the two-component model [33] (dotted line).

electrons considered in the previous section.

For comparison, Fig. 12 also shows the results of the model calculations for the open charm R_{AA} . The solid line corresponds to the charm quark energy loss because of the elastic scattering and radiative parton processes, with assumed medium gluon density $dN_g/dy = 254$ for 0 – 20 % Cu+Cu collisions [31]. The dash-dotted line shows the results of the model calculations for the D-meson energy loss with $dN_g/dy = 275$ [32], where the D-meson suppression is caused by the collisional dissociation in quark-gluon plasma. Both models, which correctly describe open heavy-flavor suppression in Au-Au collisions, predict charm meson suppression of a factor about 2 at $p_T > 5 \text{ GeV/c}$, in contrast to the J/ψ 's R_{AA} . This comparison suggests that high- p_T J/ψ production does not dominantly proceed via a channel carrying color, but rather the contribution of the color singlet channel is prevailing.

The dotted line in Fig. 12 is the result for the J/ψ 's $R_{AA}(p_T)$ in the two-component model [33], which provides quite good qualitative description of the data. Let us consider the basic assumptions of this model in more detail. First, it assumes that the p_T spectra of charmonia states ($\Psi = J/\psi, \chi_c, \psi'$) consist of two parts, direct and coalescence:

$$\frac{dN_\Psi}{p_T dp_T} = \frac{dN_\Psi}{p_T dp_T} \Big|_{dir} + \frac{dN_\Psi}{p_T dp_T} \Big|_{coal}. \quad (5)$$

The direct component is associated with hard production of charmonia in primordial N-N collisions, subject to suppression in the subsequent medium evolution due to gluon dissociation reactions in QGP and break-up by π and ρ mesons in a hadron gas phase. The

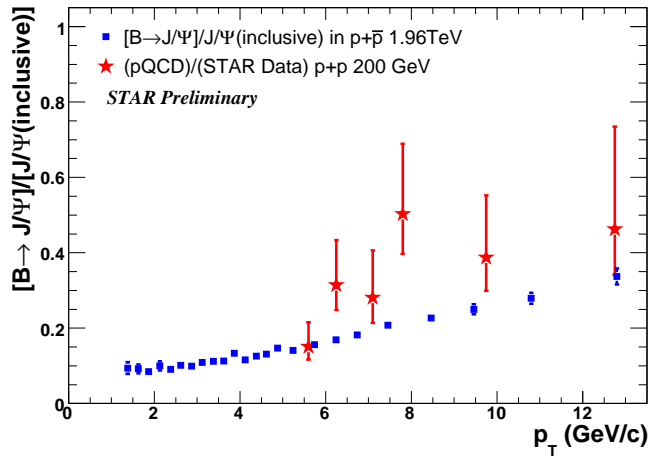


FIG. 13: (Color online) Tevatron and STAR data for the ratio of J/ψ from B-meson feed-down to inclusive J/ψ .

phase space distribution of different charmonia follows the Boltzmann transport equation, where the nuclear absorption is included in the initial conditions. Besides, the Cronin effect, consisting in multiple scattering of an initial parton on elementary constituents of the facing nucleus and leading to an increased p_T in its final state (before fusion to charmonia), is also taken into account through initial conditions for charmonia momentum distributions. The model consistently treats the leakage effect, i.e., charmonia travelling outside the fireball boundary before freeze-out are not subject to dissociation. The leakage effect reduces suppression primarily for high- p_T charmonia. The soft component is associated with the coalescence of c, \bar{c} quarks near the QCD phase boundary assuming an approximate thermalization up to c -quark momenta of $p_T \sim 2 - 2.5$ GeV/c. The medium evolution is modelled by the isentropically expanding fireball with a cylindrical volume.

Although in such a formulation the model is already quite complicated, two additional effects should be taken into account in order to reproduce an increasing trend of J/ψ 's R_{AA} at high p_T [33]. These two additional effects are: 1. Finite formation time, required to build up the charmonium wave function from a "pre-hadronic" $c\bar{c}$ pair - this effect leads to the reduction of the charmonia dissociation cross sections. 2. Feed-down from B -mesons, $B \rightarrow J/\psi$.

Fig. 13 (from Ref. [33]) shows the data from Tevatron [34] and STAR on the $B \rightarrow J/\psi$ feed-down fraction in elementary $p\bar{p}$ (p - p) collisions which is quite considerable at high p_T . After including the formation time effects and B-meson feed-down (according to Tevatron

data) into the two-component model, it is able to reproduce the increasing behavior of J/ψ 's R_{AA} at high p_T . Nevertheless, note that the recent STAR measurements on J/ψ -hadron azimuthal correlations in p - p collisions at $\sqrt{s} = 200$ GeV show that the J/ψ fraction from B-meson feed-down at high p_T is not so significant, about 13% at $p_T > 5$ GeV/c. This means that further studies are necessary, both theoretical and experimental, in order to provide a consistent picture of J/ψ production at high p_T .

-
- [1] Heavy ion physics programme in CMS, Eur. Phys. J. C **32S2**, 69 (2004).
 - [2] CMS Physics Technical Design Report: Addendum on High Density QCD with Heavy Ions, J. Phys. G **34**, 2307 (2007).
 - [3] ALICE: Physics Performance Report, V. 1. J. Phys. G **30**, 1517 (2004).
 - [4] ALICE: Physics Performance Report, V. 2. J. Phys. G **32**, 1295 (2006).
 - [5] R. Rapp and H. van Hees, Preprint arXiv: 0803.0901.
 - [6] T. Matsui and H. Satz, Phys. Lett. B **178**, 416 (1986).
 - [7] B. Alessandro et al. (NA50 Collaboration) Eur. Phys. J. C **48**, 329 (2006).
 - [8] E. Scapparini (NA60 Collaboration), J. Phys. G **34**, S463 (2007).
 - [9] R. Arnaldi (NA60 Collaboration), J. Phys. G **35**, 104133 (2008)
 - [10] K. J. Eskola, V. J. Kolhinen, and R. Vogt, Nucl. Phys. A **696**, 729 (2001).
 - [11] D. de Florian and R. Sassot, Phys. Rev. D **69**, 074028 (2004).
 - [12] A. Adare et al. (PHENIX Collaboration) Phys. Rev. C **77**, 024912 (2008); Erratum: Phys. Rev. C **79**, 059901 (2009).
 - [13] C. Lourenco, R. Vogt, and H. K. Woehri, JHEP **02**, 014 (2009).
 - [14] A. Adare et al. (PHENIX Collaboration), Phys. Rev. Lett. **98**, 232301 (2007).
 - [15] R. G. de Cassagnac, J. Phys. G **35**, 104023 (2008).
 - [16] A. A. Isayev, Proceedings of the TESHEP School (Buymerovka, Ukraine, 2008), p. 91 [arXiv:0810.4762].
 - [17] C. Silvestre (for the PHENIX Collaboration), J. Phys. G **35**, 104136 (2008).
 - [18] A. Andronic, P. Braun-Munzinger, K. Redlich, and J. Stachel, Phys. Lett. B **652**, 259 (2007).
 - [19] A. Capella, L. Bravina, E.G. Ferreira, A.B. Kaidalov, et al., J. Phys. G **35**, 104156 (2008).
 - [20] A. Capella, U. Sukhatme, C.I. Tan, J. Tran Thanh Van, Phys. Rept. **236**, 225 (1994).

- [21] N. Armesto, A. Dainese, C. A. Salgado, and U. A. Wiedemann, Phys. Rev. D **71**, 054027 (2005).
- [22] A. Adare et al. (PHENIX Collaboration), Phys. Rev. Lett. **98**, 172301 (2007).
- [23] B. I. Abelev et al. (STAR Collaboration), Phys. Rev. Lett. **98**, 192301 (2007).
- [24] D. Hornback et al. (PHENIX Collaboration), J. Phys. G **35**, 104113 (2008).
- [25] V. G. Riabov, Phys. Atom. Nucl. **72**, 509 (2009).
- [26] H. van Hees, V. Greco, and R. Rapp, Phys. Rev. C **73**, 034913 (2006).
- [27] A. Adare et al. (PHENIX Collaboration), Phys. Rev. Lett. **103**, 082002 (2009).
- [28] M. Cacciari, P. Nason, and R. Vogt, Phys. Rev. Lett. **95**, 122001 (2005).
- [29] A. Adare et al. (PHENIX Collaboration), Phys. Rev. Lett. **101**, 122301 (2008).
- [30] B. I. Abelev et al. (STAR Collaboration), Phys. Rev. C **80**, 041902(R) (2009).
- [31] S. Wicks, W. Horowitz, M. Djordjevic and M. Gyulassy, Nucl. Phys. A **784**, 426 (2007).
- [32] A. Adil and I. Vitev, Phys. Lett. B **649**, 139 (2007).
- [33] X. Zhao and R. Rapp, Phys. Lett. B **664**, 253 (2008); arXiv:0806.1239 [nucl-th].
- [34] D. E. Acosta et al. (CDF Collaboration), Phys. Rev. D **71**, 032001 (2005).